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## DEVELOPMENT OF THE THEORY AND ALGORITHMS FOR SYNTHESIS OF REFLECTOR ANTENNA SYSTEMS

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### FINAL TECHNICAL REPORT



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13. ABSTRACT (Maximum 200 words) The main objective of this work was research and development of the theory and constructive computational algorithms for synthesis of single and dual reflector antenna systems in geometrical optics approximation. During the contracting period a variety of new analytic techniques and computational algorithms have been developed. In particular, for single and dual reflector antenna systems conditions for solvability of the synthesis equations have been established. Numerical algorithms for computing surface data of the reflectors have been developed and successfully tested. In addition, efficient techniques have been developed for computing radiation patterns produced by reflections/refractions off surfaces with arbitrary geometry. These techniques can be used for geometrical optics analysis of complex geometric structures such as aircrafts. They can also be applied to determine effectively the aperture excitations required to produce specified fields at given observation points. The results have a variety of applications in military, civilian, and commercial sectors.					
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# 1 Project Description

This is the final technical report on the contract AFOSR F49620-92-C-0009; starting date - December 1, 1991, expiration date - November 30, 1994.

The initial objective of this work was research and development of the theory and computational algorithms for synthesis of single and dual reflector antenna systems. Improved synthesis techniques provide tools for design of antennas with higher efficiency, better phase and radiation pattern control, more accurate antenna performance prediction as well as improved scanning characteristics. Previous work on synthesis was primarily based on *ad hoc* calculations, which, in turn, relied on unjustifiable assumptions and/or unnecessary oversimplifications. Often, the designs were limited to rotationally symmetric and conic-section antennas.

Synthesis of reflector antennas is based on geometrical optics approximation and uses two basic physical principles: Snell's law and differential form of the energy conservation law. During the current funding period we developed a new general framework for description of the ray tracing maps and energy conservation laws for systems of reflectors and/or refractors with arbitrary geometry. Many problems in electromagnetics and optics, including various problems of analysis and synthesis of reflector systems, fit into this framework and can be successfully resolved. The developed techniques are based on differential-geometric methods and on studying analytically and computationally second order nonlinear PDE's of Monge-Ampère type expressing ray tracing and energy conservation laws. The following main results have been obtained within this general framework.

- Analytic formulas and computational algorithms for efficient computation of radiation patterns produced by reflections off surfaces with arbitrary geometry have been developed. Corresponding numerical schemes have been constructed, investigated, and implemented.
- The synthesis problem for reflector systems with two reflectors and colimated source has been completely resolved theoretically and computationally; a numerical code realizing the corresponding algorithm has been developed and implemented.
- Substantial progress has been made on the problem of synthesis of single and dual reflector systems with a point source. Here, also, the theoretical and computational aspects of the problem have been investigated and corresponding computer codes have been developed and implemented.

In terms of applications, the results obtained so far turned out to have much wider impact than it was initially anticipated. In addition to analysis and synthesis of reflector antennas, our results have applications in the following areas:

- efficient analysis of electric fields around aircrafts and similar complex structures,
- antenna performance analysis,
- analysis of aircraft radomes,
- determination of required excitations of array emitters providing prespecified levels of radiation fields,

- analysis and design of reflective/refractive systems for reshaping, redirecting, and redistributing irradiance of laser beams,
- efficient computation of radiosity in ray tracing algorithms,
- image reconstruction from measured output radiation patterns,
- allocation of resources, etc.
- superbroadband color center lasers.

These areas are of special interest to the Air Force. But the results and techniques have also a significant potential for many applications in civilian and commercial sector. In addition to the aviation industry, potential applications include optics industry, in particular, such areas as laser beam shaping and design of solid state multifrequency and superbroadband lasers. The latter are now widely used for optical communication, signal multiplexing, and fiber optics technology, as well as for laser spectroscopy, photochemistry, medicine, color microscopy, and holography.

## 2 Report on Completed Work

### 2.1 Results

1. It has been already mentioned that one of the results of this work was a development of a general framework for description and analysis of ray tracing maps and energy conservation laws for systems with reflectors of arbitrary geometry. This framework provides a general construction for representing the ray tracing map in a reflector system as a map generated by a scalar quasi-potential. Then, it is shown that the amplitude transformation of the wave passing through a sequence of reflections is represented by a second order nonlinear partial differential expression of Monge-Ampère type. Such expression is derived directly in terms of functions describing the reflectors and in this form it is particularly suitable for analytic and numerical computations of radiation patterns [1], [2], [4], [5]. (Here and below the references in square brackets are to the papers listed in the section 2.6 **Research Papers**.)

2. For Monge-Ampère type expressions arising in reflector systems with a point or collimated source we developed quite efficient computational techniques that can be used for practical analysis of existing or newly designed systems [3], [2], [6]. Specifically, these algorithms can be used to compute radiation patterns produced by scattering off objects with arbitrary geometry.

3. In the synthesis problem, one has to solve the corresponding Monge-Ampère equations under nonstandard restrictions on the class of solutions. We have been able to provide a complete theory for solving the synthesis "equations" for systems with two reflectors and a collimated source. In addition, a computational algorithm for constructing solutions numerically was developed, theoretically analysed, coded, and implemented [6]. The numerical results here form a substantial expansion and improvement of our earlier numerical algorithm published in *Numerische Math.*, 54(1988), pp. 271-293. It is worthwhile to note that the numerical algorithms for this strongly nonlinear problem do not even require the user to supply an initial approximation! The "start up" is generated by the code automatically.

4. In the synthesis problem for a single reflector antenna system with a point source we were able to prove solvability of the problem under some reasonable sufficient conditions. In this case, we derived and investigated the "linearized" version of the theory and used it to establish existence of solutions to the synthesis problem with data sufficiently close (in some appropriate norm) to the data for which a solution is known or can be constructed [1], [5].

5. The equations of the synthesis problem for a system with a point source and two reflectors are quite complex. In this problem, so far, we have investigated the linearized theory. Algorithms for computing numerically solutions to this problem have also been constructed and implemented [2]. In many practical design problems the linearized theory provides an adequate solution.

6. The computational algorithms and codes developed so far, have been organized into a package "REFSYS" implemented on a SUN workstation. This package forms a kernel of a package for analysis and synthesis of reflector systems that is currently under development.

7. The work described in items 1 and 2 has already produced results that can be used by antenna design engineers in a variety of practical problems. Mr. Ken Siarkiewicz from Computational Electromagnetic Systems Division of Rome Laboratory at Griffiss AFB encouraged us to develop a version of our software code suitable for marketing in military, civil, and commercial sectors. Some efforts in developing such software have been already made by us and we plan to expand these efforts.

8. Our approach to synthesis of reflector antennas (item 5) also attracted attention of design engineers. Mr. T. Carberry from MITRE Corp. expressed an interest in receiving a "commercial" version of our code for synthesis of dual reflector antennas. Also, Dr. Donald Bodnar from Electromagnetics Laboratory of Georgia Tech Research Institute expressed a strong interest in acquiring our synthesis codes and carrying joint research on reflector antennas and related topics.

9. The work described in items 3 - 5 can also be useful for target identification, that is, when an object needs to be recovered from measured output radiation patterns.

10. The work described in items 3 and 6 has attracted attention of researchers working on design of superbroadband color centered (SCC) lasers. The systems synthesized by our methods generate convex surfaces that can be fabricated and utilized as an essential part of an SCC laser. We continue working on this application. The work is carried out jointly with a group of researchers at the University of Alabama at Birmingham [10].

## **2.2 Interactions with Researchers at Air Force Labs and in Industry**

I am in frequent contacts with Ken Siarkiewicz from Rome Laboratory at Griffiss AFB. I visited the Lab on Oct. 27, 1992, and then again on Dec. 12, 1992. Mr. Siarkiewicz described to me a variety of problems for which our techniques provide a viable alternative to some of the classical MOM and other existing techniques in Computational Electromagnetics (CEM). He would like to incorporate our codes into the Air Force's General Electromagnetic Model for the Analysis of Complex Systems (GEMACS). In my last discussion with Mr. Siarkiewicz he pointed out that in addition to military applications the algorithms have to be useful for civilian needs, in particular, such as antennas put on automobiles for collision avoidance radar systems, automobile antennas for satellite communications, and others. This adds an additional prospective to our work.

In 1992 I visited also the Hanscom AFB, where I gave a presentation and met several people

in the Electromagnetics Division. A detailed report describing the first two visits was submitted on Nov. 3, 1992. Since then I spoke a number of times with Bob Shore. He proposed a problem connected with computation of incremental diffraction coefficients. Unfortunately, this research had to be postponed in view of the large amount of analytical and computational work connected with research on reflector systems. I will continue to be in contact with Bob Shore, Boris Tomasik and other researchers at Hanscom and hope to do some joint work with them in the future.

I have had several contacts in industry with people interested in our work. In particular, contacts have been made with researchers at MITRE Corporation. They wanted an assessment of existing algorithms for design of reflector antennas. My interactions on this subject there are with Dr. Thomas Carberry. I met T. Carberry in the Fall of 1992 at the Antenna Applications Symposium at Allerton, Ill. After the conference he contacted me and wanted to learn about our work because they are considering design of dual reflector antennas. In our subsequent contacts I provided him with an extensive and very detailed report on the available techniques, software codes, their deficiencies, effectiveness, accuracy, etc. He was interested in my work but wanted to have more or less a commercial type software package that they can purchase along with a training course in its use. I offered him to do the design for them ( via some consulting arrangements) and he was going to get back to me.

In addition, I am in contact with Dr. Donald Bodnar, from Electromagnetics Laboratory at Georgia Tech Research Institute. He is interested in using our technique for very precise analysis of antenna patterns produced by reflectors with complex geometries. I contacted Don Bodnar two years ago through the EE department of Georgia Tech, and since then I have had numerous contacts with him. He is the Chief Scientist of the Microwave and Antenna Technology Development Laboratory at the Georgia Tech Research Institute. Currently, he is the President of the Antenna and Propagation Society. His Laboratory designs and manufactures various types of antennas for military applications. Among important antenna characteristics that they are concerned with are the low efficiency and high sidelobes of existing antennas. Shaping antennas allows to produce higher gain and/or lower sidelobes. Recently, Bodnar asked me to use our technique to do a rough computation of a mirror profile for some application. I did the computations and sent him a report. Don Bodnar would like to incorporate our codes into their existing package that does physical optics analysis but is not capable to do the geometric optics analysis. A joint paper [8] on some of our results was presented at the session on Computational Electromagnetics at the IMACS Conference in July of 1994.

With the help from Dr. Arje Nachman from AFOSR a contact has been established with IITRI in Annapolis working on Electromagnetic Interference as a part of a contract with The Joint Services Center. I am presently involved in helping to develop advanced tools for computing coupling paths over general airframes.

I have been also interacting with Mr. Walter Piulle, from Electric Power Research Institute (EPRI) in Palo Alto, CA. He is involved in developing tools for nondestructive evaluations and I hope to extend our algorithms to be applicable to such problems. The EPRI's NONDESTRUCTIVE EVALUATION CENTER is using geometrical optics techniques for NDE analysis. Piulle thinks that our techniques can be used effectively for the NDE analysis and I am interacting with him on that.



## 2.3 Visits to the Air Force Labs and Participation in AFOSR Workshops

Rome Laboratories, Hanscom Air Force Base, MA, Oct. 26, 1992

Rome Laboratories, Griffiss Air Force Base, NY, Oct. 27, 1992

Rome Laboratories, Griffiss Air Force Base, NY, Dec. 12, 1992

In addition, I participated in the following workshops organized by AFOSR:

1993 AFOSR Workshop on Computational Mathematics organized by Marc Jacobs, May, 1993

AFOSR Conference on Image Reconstruction and Aero-Optics Metrology in Turbulence organized by Alan Craig, James McMichael, and Arje Nachman, AF Phillips Laboratory, Kirtland AFB, August, 1993

1994 AFOSR Grantees/Contractors Meeting in Computational and Physical Mathematics organized by Marc Jacobs and Arje Nachman, AF Phillips Laboratory, Kirtland AFB, June, 1994.

1995 AFOSR Grantees/Contractors Meeting on Electromagnetics organized by Dr. Arje Nachman, San Antonio, TX, January, 1995.

## 2.4 Other Visits

In May of 1994 I was a visiting member of the Institute for Advanced Study at Princeton. During this visit we conducted research on reflector systems with point sources. This work was performed in collaboration with Professor Luis Caffarelli, who is a permanent member of the Institute and initiated this visit. This work is currently being continued.

## 2.5 Presentations

One-hour presentation at Hanscom AFB, MA, Oct. 26, 1992

Invited 1-hour address at the Nonlinear Systems Workshop, Heidelberg, Germany, December, 1992

Special Session, National Radio Science Meeting, Boulder, Colorado, January, 1993

Invited 1-hour address at the conference in honor of Professor O.A. Ladyzhenskaya, Cleveland, OH, May, 1993

Invited talk at the International Conference on Advances in Geometric Analysis and Continuum Mechanics, Stanford, CA, August, 1993

Invited 1-hour address at the Symposium in memory of I. Bakelman, Texas A&M Univ., TX, Oct., 1993

Colloquium, University of New Mexico, August, 1993

Invited talk at the 10-th Anniversary Conference on Applied Computational Electromagnetics, Monterey, CA, March, 1994

Invited talk at a Special Session of AMS, New York, April, 1994

45-min. presentation at the Special Session on Computational Electromagnetics, IMACS Conference, Atlanta, July, 1994

Co-organizer (jointly with Drs. A. Nachman (AFOSR) and A. Peterson (Georgia Inst. of Technology)) of a special session on Computational Electromagnetics at the IMACS Conference in Atlanta, July, 1994.



## 2.6 Research Papers

1. "On the energy conservation equation in the reflector mapping problem", (with E. Newman), *Applied Mathematics Letters*, vol. 6, no. 1(1993), 91-95
2. "On the problem of synthesis of offset dual shaped reflector antennas", *Proceedings of the 1992 Antenna Applications Symposium, University of Illinois, Urbana, September, 1992*, 26 pages
3. "A formula for computing illumination intensity in a mirror optical system", (with E. Newman and L. Prussner), *Journal of the Optical Society of America, A*, vol.10, no. 9(1993), 1895-1901
4. "The ray tracing and energy conservation equations for mirror systems with two reflecting surfaces", *Computers and Mathematics with Applications*, vol.26, no.7(1993), 9-18
5. "Differential-geometric methods in design of reflector antennas", (with E. Newman), *Symposia Mathematica*, V. 35, ed.by A. Alvino, E. Fabes and G. Talenti, 1994, 205-223
6. "A new technique for synthesis of dual reflector systems", *10th Annual Review of Progress in Applied Electromagnetics*, pp. 45-52, March, 1994
7. "On analysis of reflector/refractor systems", (with E. Newman) *Proceedings of the IMACS Conference*, v.2, July 11-15, 1994, 850-853
8. "A comparison of synthesis techniques for reflector antennas", (with D. Bodnar), *Proceedings of the IMACS Conference*, v.2, July 11-15, 1994, 588-591
9. "New analytical and computational techniques for redirecting and reshaping energy flows". *Proceedings of the IMACS Conference*, v.2, July 11-15, 1994, 854-857
10. "Optical design of a two-mirror asymmetrical reshaping system and its application in super-broadband color center lasers", (with L.D. Prussner, D. Shealy, and S. Mirov), *SPIE proceedings*, V. 2263, *Current Developments in Optical Design and Optical Engineering IV*, 27-28 July 1994, San Diego, CA. 10-18
11. "Reshaping and redirecting laser beams with Monge-Ampère equations". in preparation.
12. "Weak Solutions of One Inverse Problem in Geometric Optics" (with L. Caffarelli), in preparation

The following three papers do not deal with reflector antennas. Their main purpose is to study properties of nonlinear diffusion flows. The results of these papers were useful in investigating numerical diffusion schemes. Such schemes are applied (along with others) for solving the nonlinear problems of antenna synthesis. In addition, some visualization techniques, developed in connection with this class of problems, were useful in developing visualization algorithms for our work on reflector antennas. The results are also useful for noise filtering and image enhancement in image processing. AFOSR partial support was acknowledged on these papers.

13. "Evolution of nonparametric surfaces with speed depending on curvature, II. The mean curvature case", *Communications on Pure and Applied Mathematics* (with N. Uraltseva), vol. 46, no. 1(1993), 97-135
14. "Self-similar solutions and asymptotic behavior of flows of nonparametric surfaces driven by Gauss or mean curvature, *Symposia in Pure Mathematics*, vol.54, part 1, American Mathematical Society, 1993, pp. 389-402
15. "Evolution of nonparametric surfaces with speed depending on curvature, III. Some remarks on mean curvature and anisotropic flows, (with N. Uraltseva), in "Degenerate Diffusions", ed. by W.-M. Ni, L.A. Peletier, and J.L. Vazques, *IMA Volumes in Mathematics and its Applications*, vol.26, no.7(1993), pp. 141-156

## 2.7 Graduate Students

One of my graduate students, Elsa Newman, received \$13,500.00 award from American Association of University Women to study "Some direct and inverse problems in Geometric Optics", 1992-93. In May of 1993 she successfully defended at Emory Univ. her Ph.D. thesis "Some problems in geometric optics: reflector synthesis and analysis".

Currently I am supervising two graduate students, one of which is involved in the work on reflector antennas.